Tsunami Early Warning System: Deep Sea Measurements in the Source Area

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Abstract

In the framework of the EU project NEAREST, a new Tsunami Early Warning System (TEWS), able to operate in tsunami generation areas, was developed and installed in the Gulf of Cadiz. The TEWS is based on the abyssal station GEOSTAR, placed above a major tsunamigenic structure, and on three seismic centres of Portugal, Spain and Morocco. The core of the system is a tsunami detector installed onboard of GEOSTAR. The tsunami detector communicates with a surface buoy through a dual acoustic link. The buoy is connected to land stations via satellite link. The system was designed for near-field conditions and successfully operated from August 2007 to August 2008, 100 km SW of Cabo de Sao Vincente (Portugal). A new mission started on November 11th, 2009 in the same location. The tsunami detection is based either on pressure events either on seismic events. The bottom pressure data are analysed in real-time at the seafloor by a new tsunami detection algorithm, which can recognize tsunami waves as small as one centimetre. At the same time it was developed a new theoretical approach to account for tsunami generation in compressible water and in presence of a porous sediment. This model showed that hydro-acoustic waves, travelling much faster than the tsunami, are caused by the seafloor motion. These waves can propagate outside the generation area and are characterised by a modulation carrying valuable information on the seafloor motion, which can be recovered from their first arrival.

1 Introduction

Tsunami waves are dangerous and potentially destructive waves generated by different mechanisms, as submarine earthquakes, sub-aerial and submarine landslides, volcanic eruptions, meteorite impacts or moving barometric variation. Among these mechanisms, the most common is due to earthquake as reported by the catalogues [1, 2, 3]. Tsunamis can travel long distances with low attenuation, at speed depending on water depth. The disastrous Sumatra event on December 26th, 2004 [4] and the event of Samoa Islands on September 29th, 2009 are recent examples

of the tsunami threat. As a consequence of those tragedies, the development of reliable Tsunami Early Warning System (TEWS) received a strong impulse both from scientific and civil institutions.
A TEWS is presently based on a seismic trigger and on the direct measurement of the anomalous wave in deep sea or, alternatively, on the observation of its effect in the vicinity of the shore. The current systems are based on bottom pressure recorder and seismic sensors network, as DART and DART II [5], DONET [6] and GITEWS [7]. The common feature of these TEWS is the presence of the pressure sensors, used to monitor the pressure perturbations at depth, including travelling tsunami waves [8]. In this case the tsunami signal has to be identified among other pressure perturbations, which can have greater amplitudes and that are caused by various effects as barometric pressure changes, wind waves, tides, boats travelling nearby the sensor location, sea floor acceleration due to seismic events, salinity and temperature variations, and marine currents. All these effects are considered as noise and have to be filtered out to obtain a detailed measurement of the tsunami wave.
When tsunami waves are generated by sources far from the coast these TEWS should operate with good results, but when the tsunamigenic sources are located near the coast they show strong limitations because of the very short time allowed to issue an effective warning. Unfortunately, the highly populated coasts of the Mediterranean are all characterized by a similar condition. To minimize the elapsed time between generation and identification of the tsunami wave, NEAREST project (http://nearest.bo.ismar.cnr.it) proposed to monitor directly the potential tsunamigenic structures. This poses the problem of the tsunami wave detection in near field condition where, in addition to the effects mentioned above, the tsunami signal is masked by dynamics and kinematics effects induced by sea floor motion.
We choose the Gulf of Cadiz as a test region for the Tsunami Warning System able to operate in generation area, because this region is characterised by well confined potential tsunamigenic sources [8]. In the framework of NEAREST, a prototype of a new instrument, called “tsunameter”, specifically designed to operate well in near-field conditions has been developed and installed above a major tsunamigenic structure, off the Gulf of Cadiz, at water depth of 3200m. The tsunameter is installed onboard the abyssal station GEOSTAR developed by INGV through previous EU funding. The station communicates with a surface buoy through a dual acoustic link: the buoy is connected to land stations via satellite link. This system operated from August 2007 to August 2008 offshore Cabo de Sao Vincente (Gulf of Cadiz) and a new mission started in the same region on November 2009. The need to better understand the tsunami generation process favoured the development of a new conceptual model taking into account water compressibility and the presence of porous seabed [9].

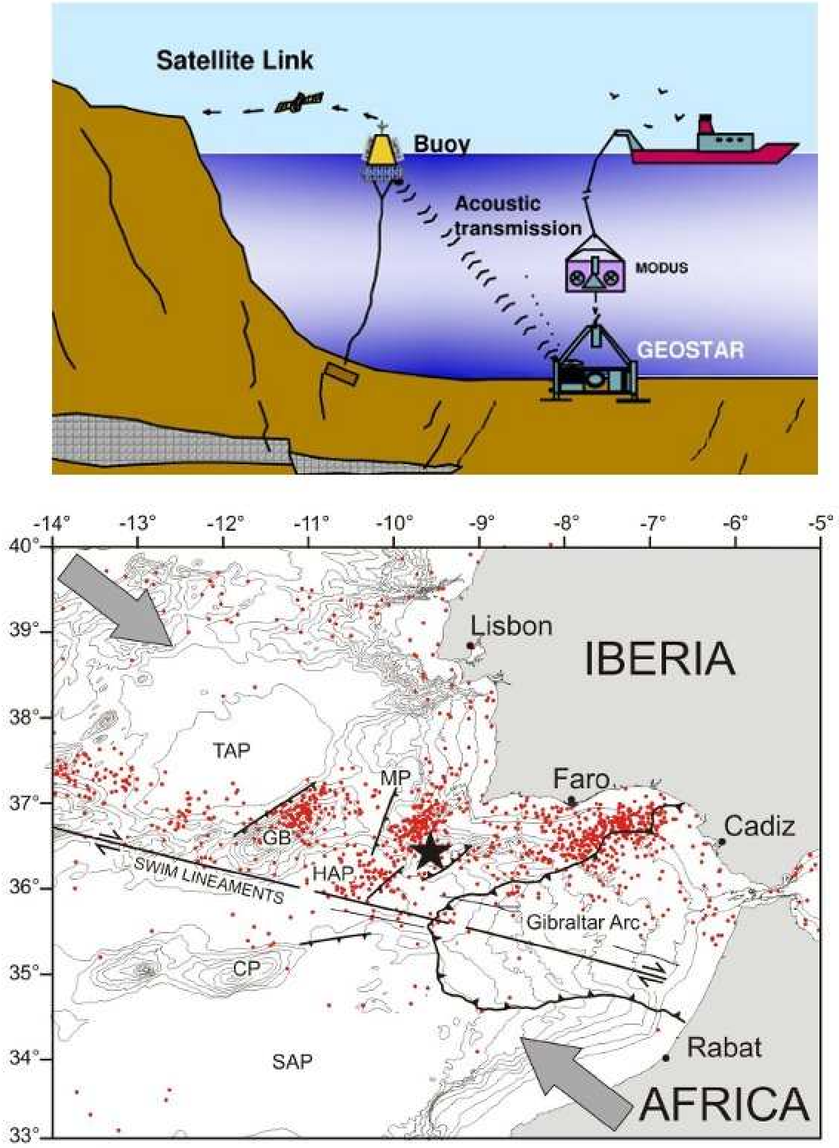
2 Tsunameter Components and Characteristics

The tsunameter is made by a set of devices, bottom pressure sensor, accelerometers, seismometer connected to a processing unit hosted onboard of GEOSTAR. The tsunameter is in charge of the data processing and of the identification of the tsunami wave, if present. In addition, the tsunameter communicates in a two-way mode by mean of a surface buoy, through a dual acoustic link. The surface buoy is connected to control land stations thanks to a satellite dual link. Figure 1a shows the tsunameter communication scheme. The seafloor station is designed to operate in three different ways:

1. Mission mode: two periodic messages are sent to the surface buoy every 6 hours containing, respectively, the sensors status and sampled data.
2. Event mode: it is triggered by a seismic or pressure event, the data relevant for the warning purpose are sent to the surface buoy.
3. Idle mode: a power saving mode during which the station can be reconfigured and restarted.

The data acquired by the tsunameter are real-time processed at the sea-floor by dedicated algorithms and are cross-checked in order to send a tsunami warning message. In particular the tsunami detection procedure is based on a double check on both pressure and seismic events. The seismic data are processed using a Short Term Average over Long Term Average (STA/LTA) algorithm. The bottom pressure data are analysed using the new tsunami detection algorithm developed within NEAREST and composed by a chain of different filters. Each filter can be included or excluded by the processing routine. The application of this filtering cascade to the bottom pressure time series reduces the dynamical range of the sea level perturbations, from about 1-3 meters of equivalent water to few centimetres, obtaining tsunami detection sensibility better than 1cm. Finally, the filtered bottom pressure data are matched against an appropriate tsunami amplitude threshold. Once exceeded a warning message is issued.

More details about the GEOSTAR abyssal station is given in Figure 2: inset a) shows a picture of the station with the upper module MODUS that guide the GEOSTAR during the deployment, while inset b) shows a scheme of the real time communication from sea floor to the land stations.



a) b)

Figure 1: Inset a): Communication scheme of the tsunameter. Inset b): Gulf of Cadiz morpho-tectonic map. Contour line every 500m from GEBCO digital Atlas; Black star: GEOSTAR Location; Grey arrows: relative movement direction between Africa and Iberia plates; TAP: Tagus Abyssal Plain; HAP: Horseshoe Abyssal Plain; SAP: Seine Abyssal plain; GB: Gorringe Bank; MP: Marques de Pombal Structure; Swim Lineaments from [10] representing the probable modern plate boundary between Africa and Iberia; black line with triangles: major thrust fault present in the area.

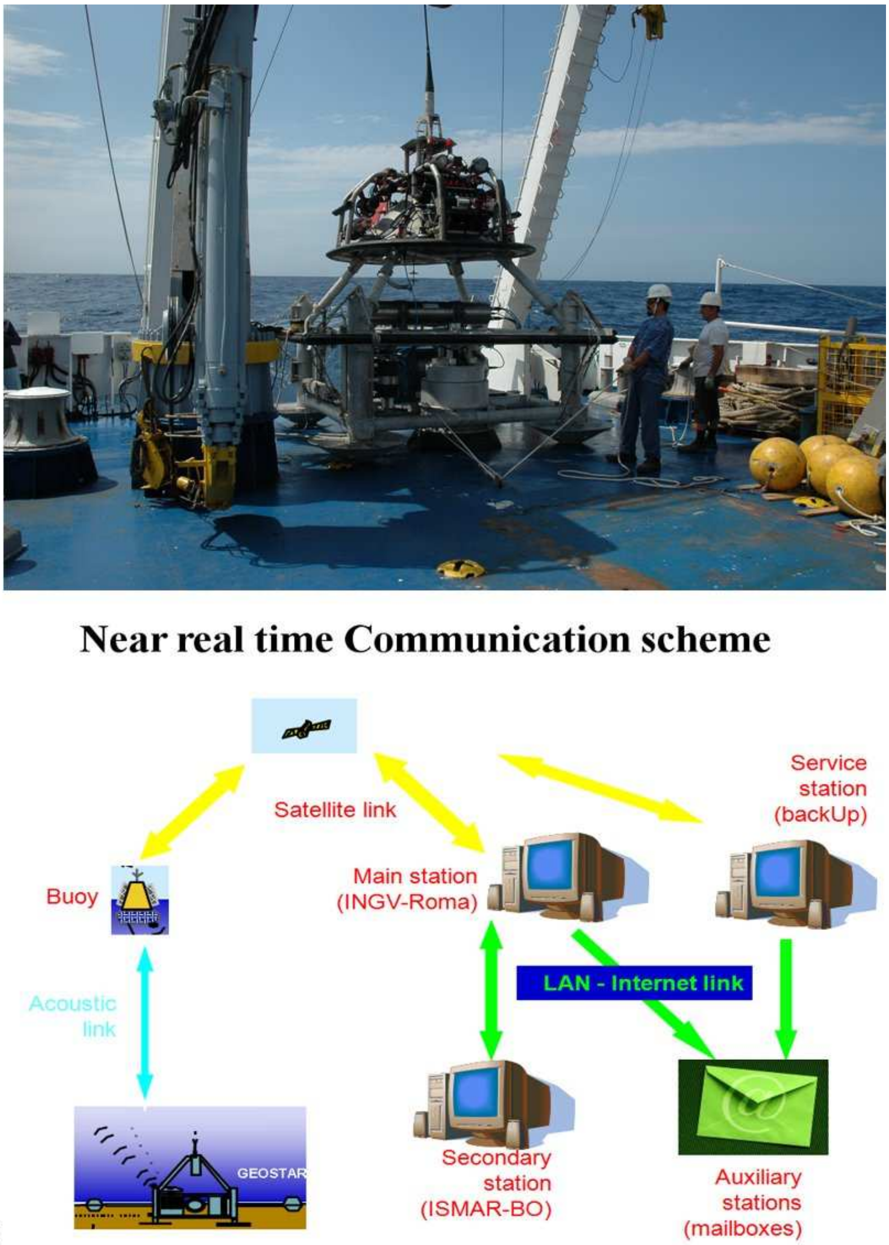
a)
b)


Figure 2: Inset a): Picture of GEOSTAR with the upper module MODUS. Inset b): Tsunameter real time communication scheme.

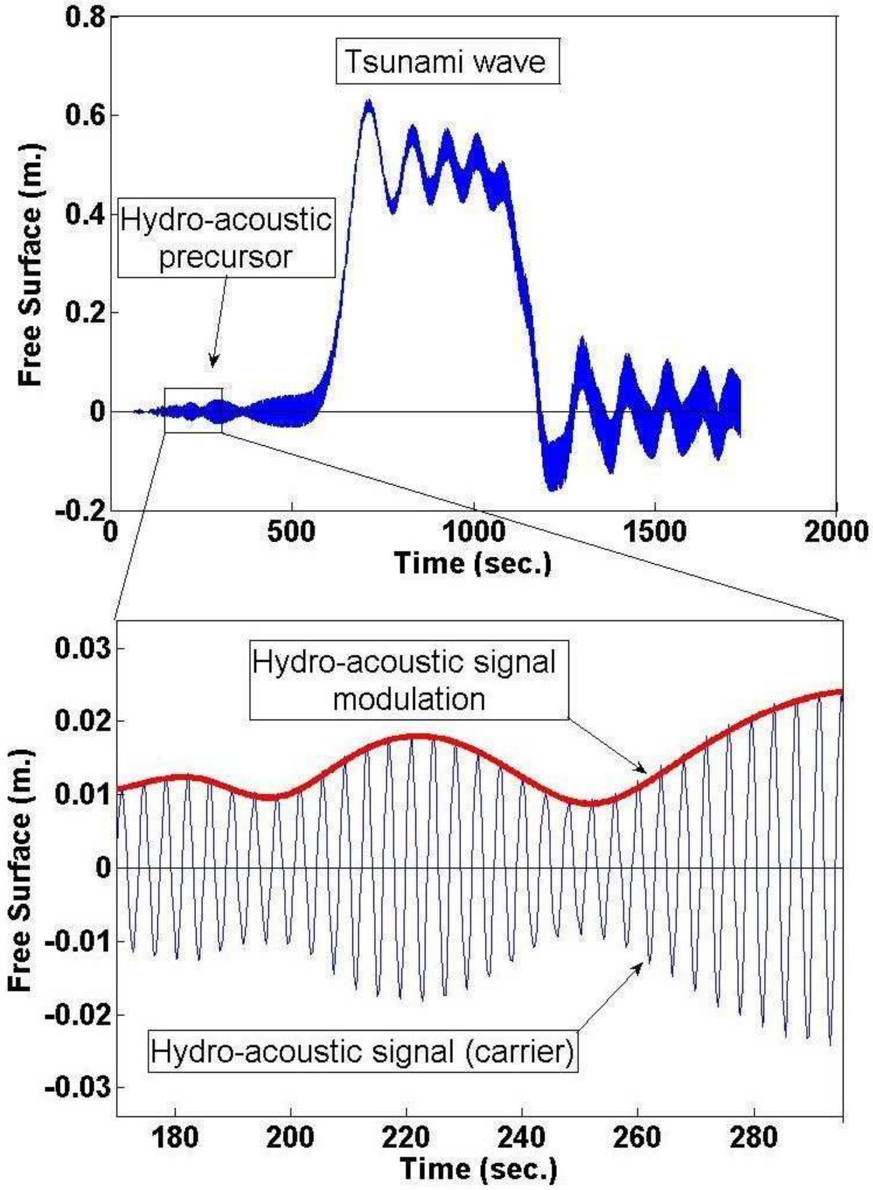


Figure 3: The upper inset represents the free-surface plots at fixed observation point located at 100 km from the source, while the lower inset is the zoom of the first part of the acoustic signal with its modulation.

3 NEAREST pilot experiment in the gulf of Cadiz

The SW Iberia is a tsunami prone area as testified by the 1755 Lisbon earthquake which caused a devastating tsunami affecting all the cities facing the Gulf of Cadiz and reaching the coasts of Great Britain and Caribbean islands. This region is situated at the Eastern end of the Atlantic Eurasia-Africa plate boundary with convergence rate of 4 mm$\cdot$y^{-1} [11] and has seismic activity concentrated along a belt going from the Gibraltar Strait to the Azores. The geological structures of this area were studied and mapped in the framework of NEAREST and during the previous EU project BIGSETS and the ESF project SWIM. It is now well established that the main tsunamigenic tectonic sources are located between the long ESE-WNW strike-slip faults, the SWIM lineaments showed in Figure 1b [10] and the Iberian coastline.
In the framework of NEAREST, a prototype of the tsunameter described in the previous paragraph was installed onboard of the multi-parametric observatory GEOSTAR and successfully deployed offshore Cabo de Sao Vincente. The station was placed above an active, potentially tsunamigenic structure, the Marques de Pombal Structure [12, 13] at a depth of 3200 m. on August 25th 2007. The system operated for one year. The bottom pressure signal was processed by the new tsunami detection algorithm.
Recently, on November 11th 2009, the abyssal station, with the tsunameter onboard, was deployed again in the same region where it is presently operating.

4 Future perspectives for hydro-acoustic precursor?

A challenging and very promising frontier for scientific research in the field of the Tsunami Early Warning is the ”hunt” for a potential tsunami precursor. Starting from the pioneering work of Peltier and Hines [14] and passing through the work of Artru et al. [15] many attempts have been made to find the possible tsunami precursors induced in the atmosphere, while a first attempt to look for a hydro-acoustic precursor in the water column was made by Okal et al. [3], who proposed to use the T-waves for tsunami warning purpose. These waves are the high-frequency acoustic signal caused by the earthquake and channelled in the seawater by SOFAR wave guide.
More recently, Chierici et al. [9] developed a theoretical work concerning tsunami generation taking into account the water compressibility and the effect of a porous sea bed. They showed that modulated hydro-acoustic waves are generated in the water layer by the sea-floor motion. The presence of the porous sediment acts as a “natural” low pass filter and allows the hydro-acoustic waves to propagate up-slope and outside the generation area with low attenuation. The main and surprising feature of these waves is their modulation, which carries information on the seafloor motion and source parameters. The existence of these waves was firstly observed during the Tokachi-Oki 2003 event [16], when two pressure sensors, located within the generation area, detected an hydro-acoustic signal generated by the seafloor motion induced by the earthquake. The model of Chierici et al. correctly reproduces the

measured frequency and amplitude of the signal. These acoustic waves travel with speed at least seven time greater than the tsunami waves well preceding its arrival. Information about the source parameters, for instance the sea floor motion velocity, the source extension and the source displacement may be extracted from the very first pulses of the modulation. Thanks to these results the modulation of these acoustic waves may act as a “hydro-acoustic tsunami precursor” and could be integrated in a new generation of Tsunami Early Warning System. Figure 3 shows an example of this hydro-acoustic signal, obtained using the model developed by [9]. The upper inset represents the water surface disturbance for a fixed observation point at 100 km distance from the source. The lower inset shows the hydro-acoustic precursors and its modulation characterised by its pulses.

5 Conclusions

In the framework of EU project NEAREST, a new tsunameter designed to operate in a generation area was developed and installed off the Gulf of Cadiz, where successfully worked for one year. The system has been recently redeployed at the same site. The tsunameter is able to take into account the dynamical and kinematical effects due to the sea floor motion biasing the tsunami signal measurements and identification.

A key role in the development of a future and more effective Tsunami Early Warning System designed for near-field conditions, could be played by potential tsunami precursors. On behalf of NEAREST project Chierici et al. found, in a theoretical work, that modulated waves, which are induced in the water column by the sea floor motion, might be regarded as “hydro-acoustic tsunami precursors”. These waves travel at speed much greater than the tsunami wave, propagating outside the generation area with low attenuation and carrying relevant information on the sea floor motion. The measurement and analysis, in a real ocean environment, of this hydro-acoustic signals is the needed step in order to validate the use of this acoustic signal for tsunami early warning purpose.

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